WIND OBSERVATIONS OF ANOMALOUS COSMIC RAYS FROM SOLAR MINIMUM TO MAXIMUM

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ABSTRACT

We report the first observation near Earth of the time behavior of anomalous cosmic-ray N, O, and Ne ions through the period surrounding the maximum of the solar cycle. These observations were made by the *Wind* spacecraft during the 1995-2002 period spanning times from solar minimum through solar maximum. Comparison of anomalous and galactic cosmic rays provides a powerful tool for the study of the physics of solar modulation throughout the solar cycle.

Subject headings: cosmic rays: general – interplanetary medium – Sun: magnetic fields – Sun: solar wind

1. INTRODUCTION

The anomalous cosmic rays (ACRs) were first observed in studies of the energy spectra of ions in the 10-50 MeV amu^{-1} region during solar quiet times in the 1970's (Garcia-Munoz et al. 1973; Hovestadt et al. 1973; McDonald et al. 1974). They were originally thought to consist only of the elements He, N, O, and Ne with anomalous abundances such as He/O ~1 and O/C >20. Fisk, Kozlovsky, & Ramaty (1974) soon proposed that the ions came from elements with high first ionization potential (FIP) that are neutral in the interstellar medium. The neutral atoms easily penetrate the heliospheric magnetic fields and approach the Sun where they are photoionized and "picked up" by the solar wind. The pickup ions are then carried out by the solar wind to the heliospheric termination shock where they are preferentially accelerated because they are injected into the shock with velocities up to twice that of the solar wind (Pesses, Jokipii, & Eichler 1981). Intensities of the accelerated ACRs are then modulated as they propagate back to 1 AU against the flow of the solar wind. Properties of ACRs have been reviewed by Klecker (1995), Lee (1996), Cummings & Stone (1996), Leske (2000), le Roux (2001), and Heber & Cummings (2001).

The effect of the solar cycle on ACR observations at 1 AU is extreme. Not only are ACR intensities reduced by factors of ~100, but there is an increasing presence of very large solar energetic-particle (SEP) events in which O intensities can rise above the ACR intensities by many orders of magnitude. At solar maximum, quiet periods are rare and limited in duration. For this reason, nearly all ACR measurements have been made near solar minimum and the behavior of the ACRs at solar maximum has not been known. In fact, it is common to say that the ACRs "disappear" during each solar maximum and their "recovery" afterward is often welcomed like the first robin of spring (e.g. Hasebe et al. 1994).

In this letter, we report, for the first time, the intensities of ACRs during their full decline from solar minimum to solar maximum and their time variations during solar maximum.

2. OBSERVATIONS

Measurements of ACR intensities are made with the Low-Energy Matrix Telescope (LEMT) in the Energetic-Particles Acceleration, Composition, and Transport (EPACT) experiment on the *Wind* spacecraft launched on 1994 November 1 (von Rosenvinge *et al.* 1995). The response of LEMT to ACR ions and the ACR spectra and time behavior during solar minimum were discussed at length by Reames (1999) and by Reames & Ng (2001). The LEMT geometry factor of 51 cm^2 sr is ideal for measuring low-intensity ACRs even in quiet periods of limited duration.

To exclude SEP events and select quiet periods, one can place an upper bound on low-energy H or He ions, making use of both the higher relative abundance of these ions and the steeper energy spectra in SEP events. However, if one uses a strong criterion, such as that used to study rare ions during solar minimum (Reames 1999), one finds that there are no quiet times at all at solar maximum. Therefore, we have relaxed the criterion and now to exclude 8-hour periods with more than 2×10^{-4} He ions (cm^2 sr sec MeV amu^{-1})$^{-1}$ in the 2.0-3.7 MeV amu^{-1} interval.

Figure 1 shows intensities of the resultant "quiet-time" O at various energies as a function of time. To accumulate an adequate quiet-time period, the time intervals for the points in Figure 1 are taken as 8 27-day solar rotations or 216 days. At times after the year 2000, the intensities of O below ~6 MeV amu^{-1} begin to depart from the trend of the higher-energy points; we believe that these low-energy increases result from residual SEP background.

Figure 2 shows the resulting O spectra, with the energy intervals removed that are most affected by SEP background. Dates labeling each of the spectra in Figure 2 are the dates at the center of each 216-day interval. Spectra are shown from the peak at solar minimum (1997 July 5) through the valley at solar maximum (2001 January 21) and two additional spectra during the rise after solar maximum are also shown (2001 August 25 and 2002 March 29).

The estimated contribution of galactic cosmic rays (GCRs) to the spectrum of O for the 216-day interval centered on 2001 January 21 is shown as a dashed line in Figure 2. The power-law slope of this line, 1.04±0.08, is derived from a least-squares fit to the quiet-time *IMP 8* He spectrum between 28 and168 MeV amu^{-1}, shown in Figure 3. This spectrum is then normalized to the lowest-energy (76 MeV amu^{-1}) O point observed by the Cosmic-Ray Isotope Spectrometer (CRIS) in the *ACE* spacecraft. A spectrum increasing linearly with energy is the theoretically expected equilibrium form of the modulated GCR spectrum at sufficiently low energies. This analysis suggests that at solar minimum, 22% of the O in the 8-10 MeV amu^{-1} interval comes from GCRs and 78% comes from ACRs. Figure 3 also shows the C spectrum derived from LEMT in the 10-18 MeV amu^{-1} region; this C is expected to come entirely from GCRs. The C measurements suggest that we have overestimated the GCR contribution to O at low energies.

Sollitt et al. (2001) using data from the SIS Detectors on ACE measured very similar O intensities over this same period. Their quiet-time data for the last half of 2000 showed at turn-up at 8 MeV amu^{-1} similar to our observations. However, they concluded that they were unable to rule out solar and interplanetary O as the cause of this turn-up. The LEMT response at 6 MeV amu^{-1} rules out a significant contribution from solar/interplanetary O and is consistent with the presence of ACR O at this time. In fact, the low-energy coverage of LEMT is key to establishing the evolution of the flat ACR spectra during the entire period.

Figure 4 shows the time evolution of the observed, mostly-ACR O in the 8-18 MeV amu^{-1} interval together with the scaled intensities of the Climax neutron monitor (http: //ulysses.sr.unh.edu/NeutronMonitor/neutron_mon.html) and the 169-382 MeV amu^{-1} GCR intensity of He measured on the *IMP8* spacecraft, all averaged in 54-day intervals. This neutron-monitor scaling is often used to compare the modulation of anomalous and galactic cosmic rays (Leske 2000) and a suitable scaling has been chosen for the GCR He. Note that the minimum of the neutron-monitor intensity seems to come about 3 time intervals (~5 months) before that of the ACRs, but the times of the GCR He and ACR O intensity minima agree well.

In Figure 5 we compare the time evolution N, O, and Ne in the same energy/nucleon interval. Because of the high He/O ratio in SEP events, ACR He can be measured only at times near solar minimum, as shown in the figure. Ne, with the lowest charge-to-mass ratio Q/A, appears to be modulated less than N or O, as expected. At a given velocity, ions with the highest magnetic rigidity (lowest Q/A) are modulated least. However, the uncertainties in N and Ne are large at solar maximum.

3. DISCUSSION AND CONCLUSIONS

The depth of cosmic ray modulation through the solar maximum period of 23 (as defined by climax neutron monitor data) was larger than that of cycle 20, comparable to cycle 21, and less than cycle 22. The study presented here clearly establishes the presence of a highly modulated ACR O component over the 8 – 14 MeV amu^{-1} energy interval.

Detailed theoretical calculations are required to fully understand the modulation we have shown. However, the relative time-history of ACR O and GCR He (Figure 4) suggest that the character of the modulation process from solar minimum to solar maximum was very similar for these two components. Thus, we conclude (a) that there was not a drastic change in the ACR intensity at the termination shock at these energies over this period and (b) that a significant part of the modulation for GCRs for this phase occurred between 1 AU and the termination shock (see also Fujii & McDonald 1995, Webber 2001, and McDonald et al. 2002).

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FIGURE CAPTIONS

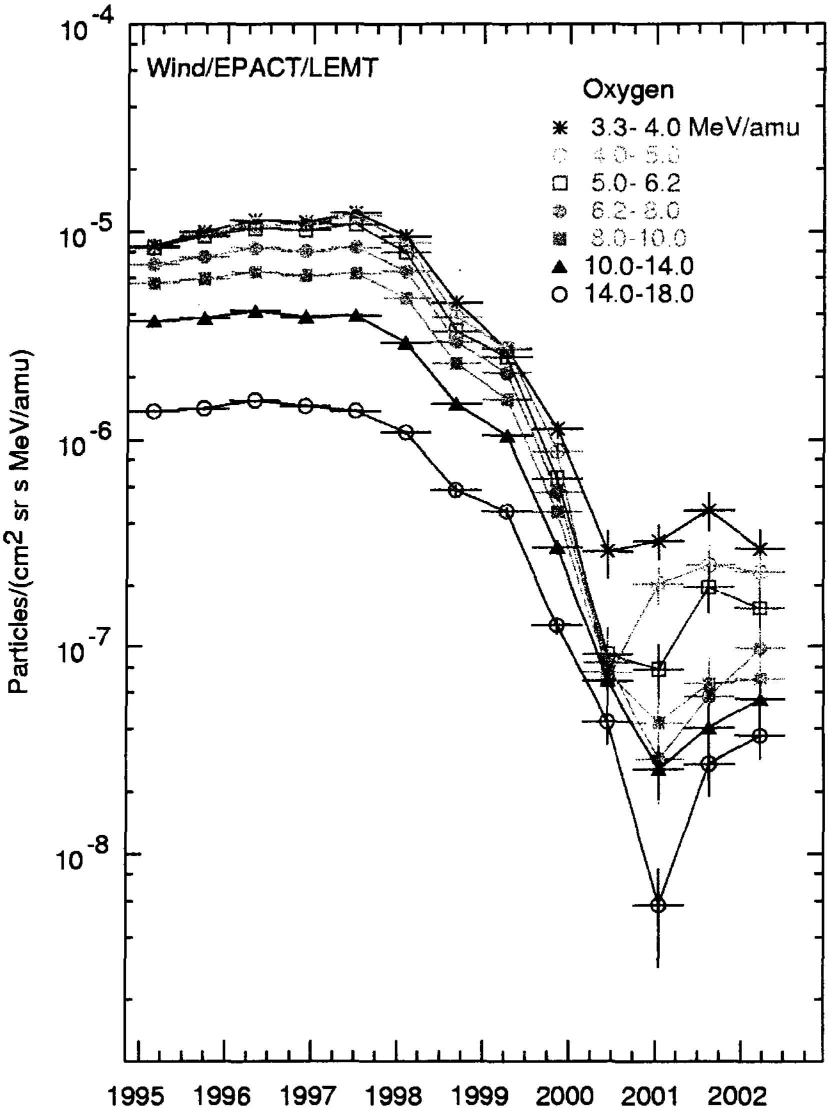
Figure 1. Intensities of O at various energies are shown as a function of time in 8-rotation (216-day) averaging intervals. Energies below 6.2 MeV amu^{-1} are affected by SEP background during solar maximum.

Figure 2. Energy spectra of 8-18 MeV amu^{-1} O in 216-day intervals are shown from solar minimum through solar maximum. Spectra are labeled by the date at the midpoint of each interval and spectral regions affected by SEP background have been omitted. The extrapolated intensity of GCR O is also shown (see text).

Figure 3. The *IMP 8* He spectrum (blue crosses) and least-squares fit to it are normalized to the 76 MeV amu^{-1} O intensity (green filled circles) observed by CRIS to estimate the GCR O contribution at low energies. This fit line may be compared with the spectra of C and O observed by LEMT. All data come from the 216-day interval centered on 2001 January 21.

Figure 4. The time dependence of the 8-18 MeV amu^{-1} O in 54-day intervals is compared with scaled values of GCR data from the Climax neutron monitor and 169-382 MeV amu^{-1} He.

Figure 5. The time dependence of the intensities of He at 6.2-8 MeV amu^{-1} and N, O, and Ne at 8-18 MeV amu^{-1} are compared. He is measured only near solar minimum. Note that Ne is modulated less than N at solar maximum as expected from its lower value of *Q/A*.



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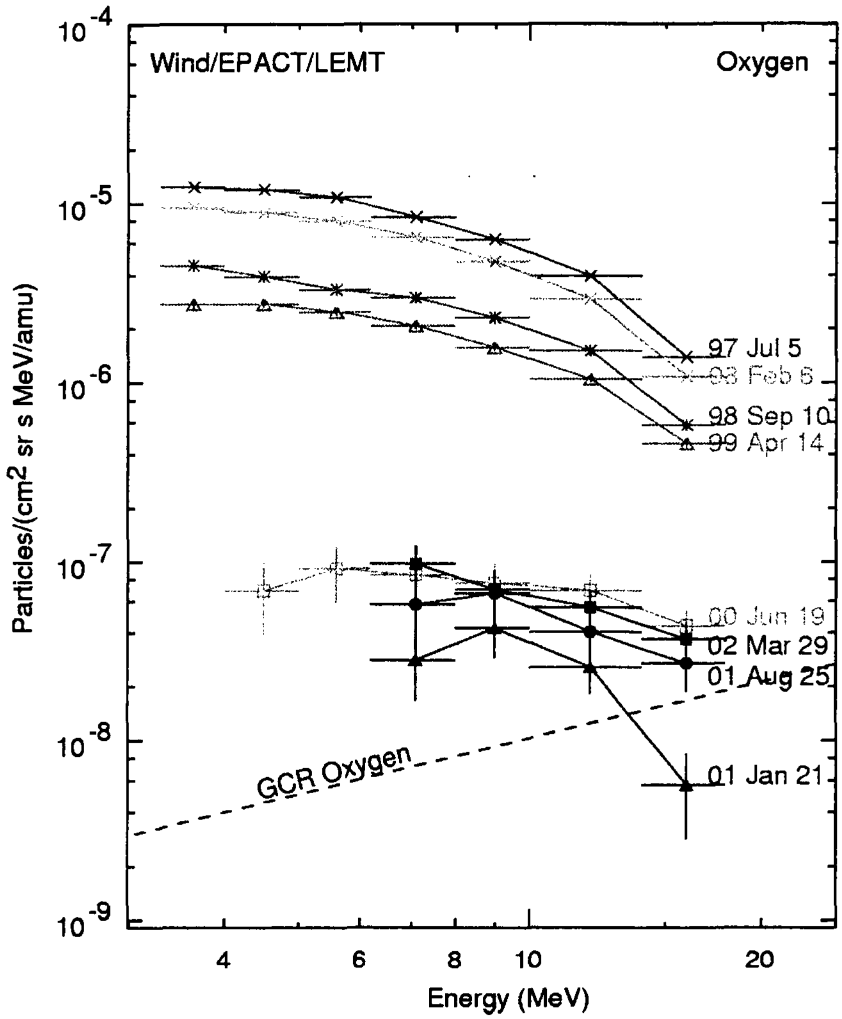

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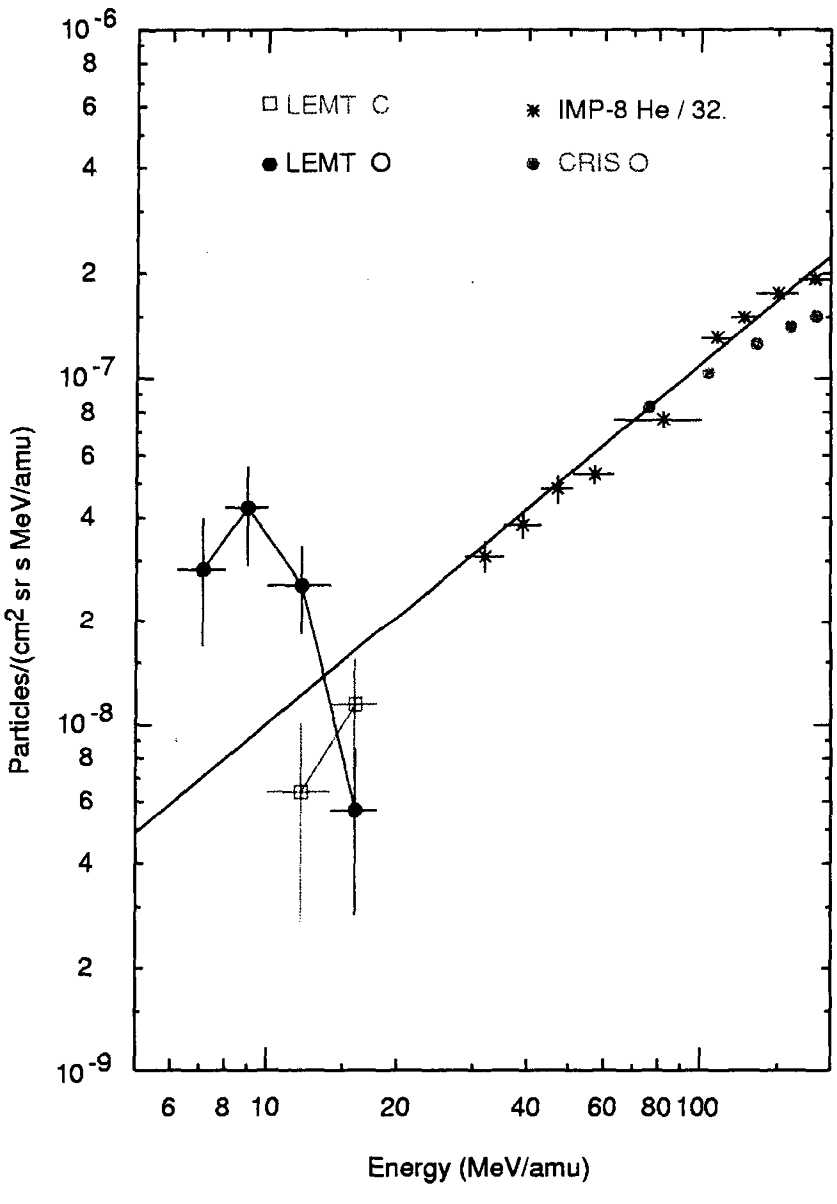

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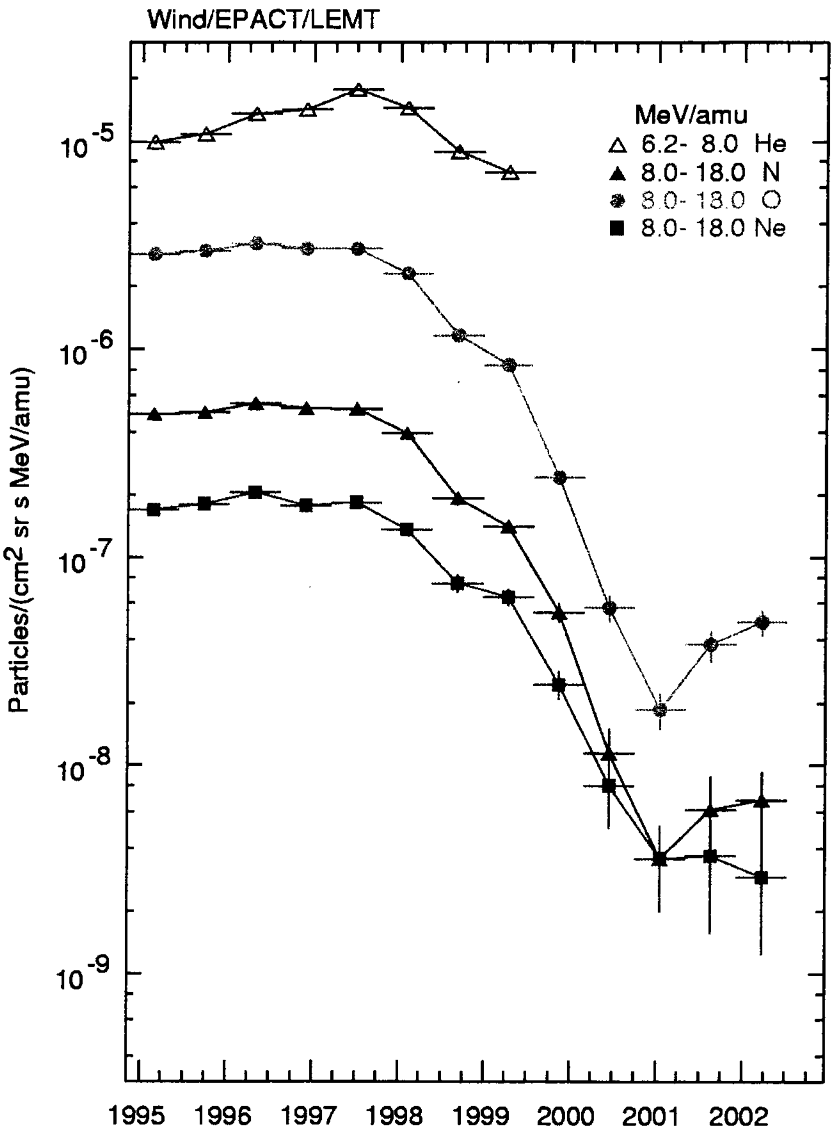

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